

High Temperature Combustion System (CPS #: 14223)

Arvind Atreya (PI)

Tershia Pinder & Hyoseok Lee (Ph.D. Candidates)

University of Michigan, Ann Arbor, MI 48109

Acknowledgements

Bob Gemmer, Fran Geurink, John Trieloff

DOE, State of Michigan Energy Office, & UM



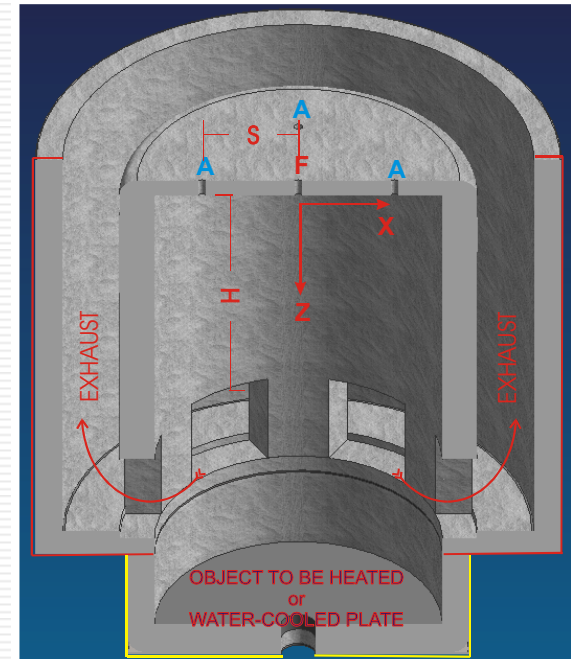
High Temperature Combustion System (CPS #: 14223)

Goal: To significantly improve energy efficiency and reduce emissions in furnaces by using high temp. radiative homogeneous combustion and develop optical detection technology for real-time control.

Challenge: Flue gas heat recovery, Oxygen enriched combustion, Flue gas recirculation, Homogeneous combustion (DOC, FLOX), Highly radiative combustion, NO_x reburn, etc. all show promise to increase energy efficiency and reduce emissions. How do we combine them in a single system to increase flame stability and turn-down ratios?

Benefits: Energy savings of 2 Quads/year \Rightarrow \$10 billion in cost savings, 30 MtC in Carbon reduction.

FY05 Activities: Furnace measurements and calculations (modify code) for various v , d , S , H and fuel and oxidizer concentrations and stoichiometry; Develop furnace control methodology based on the measurements.



Cut-away view of the furnace showing high temperature ceramic liners

Participants: State of MI Energy Office, University of Michigan, Weldaloy Products Company, E3M Inc., Kettering University & T. Borton Assoc., Inc.



High Temperature Combustion System (CPS #: 14223)

Barrier-Pathway Approach

Barriers

- Low energy efficiency & high pollutant formation from furnaces due to:
 - 1.Flue gas heat loss.
 - 2.Low flame radiation.
 - 3.Excess N₂ in air.
- Non-uniform heat flux & low productivity.
- Inability to use of low calorific value fuel.
- Multi-fuel capability.
- O₂-free atmosphere to prevent oxidation.
- Poor turn-down ratios.

Pathways

- Capture flue gas enthalpy to highly preheat O₂-enriched air and fuel.
- Develop a 3-D transient model for furnaces.
- Flue gas recirculation.
- Highly radiative homogeneous combustion.
- Buoyant recirculation for flame stability.
- Optical detectors for real-time control.

Critical Metrics

- Test furnace radiative fraction > 0.6 and Homogeneous Combustion
- Modify a 3-D transient code developed by NIST.
- Visible and infrared detectors for furnace control.
- Adoption by the industry.

Benefits (est.)	2020
Energy Savings	2 Quads
Cost Savings	> \$10 Billion
Carbon Reduction	30 MtC



Technical Presentation Outline

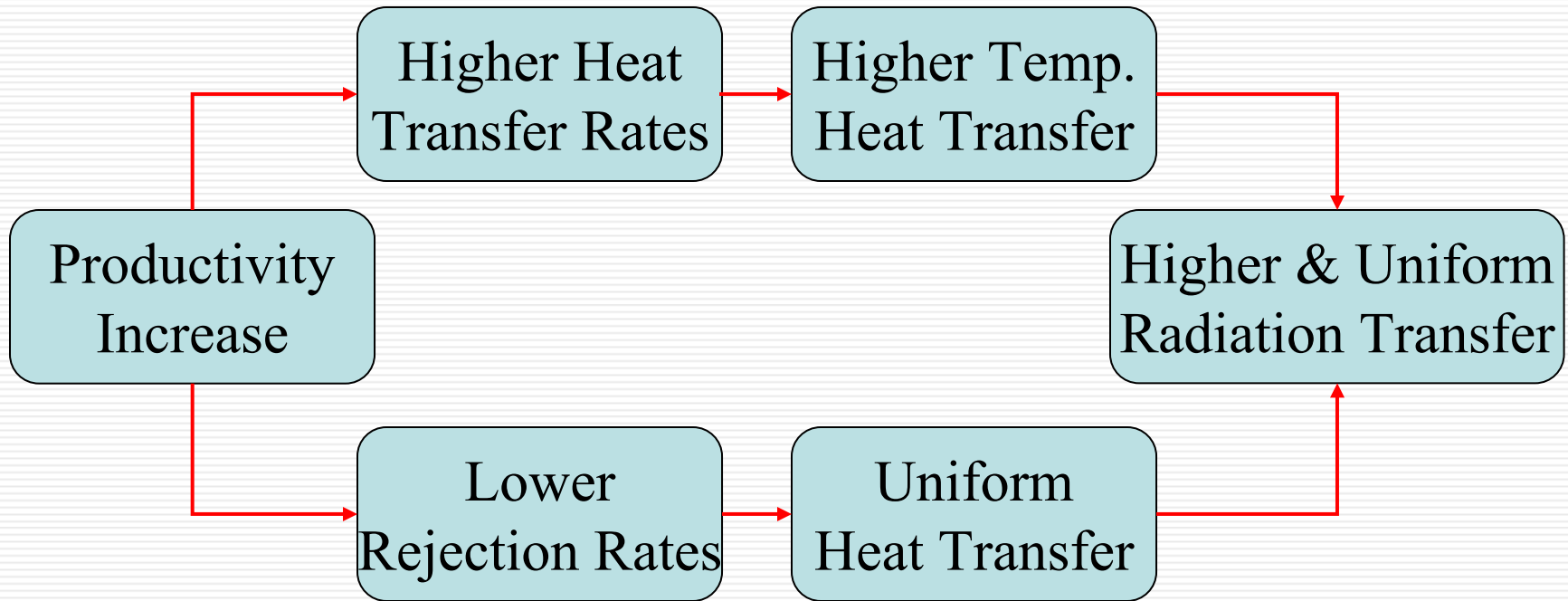
- Goals and Objectives
- Background
- Introduction to Furnace Design
- Cold Flow Water Experiments
- Description of the Experimental Furnace
- Hot Flow Computer Modeling
- Conclusions



Goals and Objectives

Develop a combustion system to –

- 1. Decrease natural gas consumption for the same production.
Or increase productivity for the same gas consumption.*
- 2. Reduce emissions.*

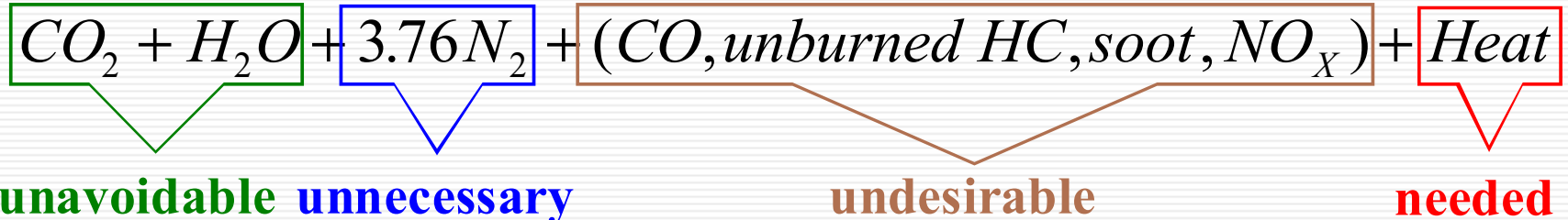


We also need better controls and turn-down ratios.



Background

Consider typical hydrocarbon combustion in air:



- Clearly, reducing exhaust of hot N_2 will increase energy efficiency. N_2 is also not needed for combustion – it only serves to produce NO_x .
- However, N_2 cannot be completely removed economically – *membrane separation technology can economically provide up to 45% oxygen-enriched air.*



Background

- Disadvantage – 45% O₂ considerably increases the flame temperature and the remaining N₂ is sufficient to produce copious amounts of NO_x.
- Advantage – O₂-enriched, fuel-lean combustion will reduce CO, unburned HC and soot.
- Disadvantage – But, fuel-rich conditions needed for reburning NO_x to N₂.

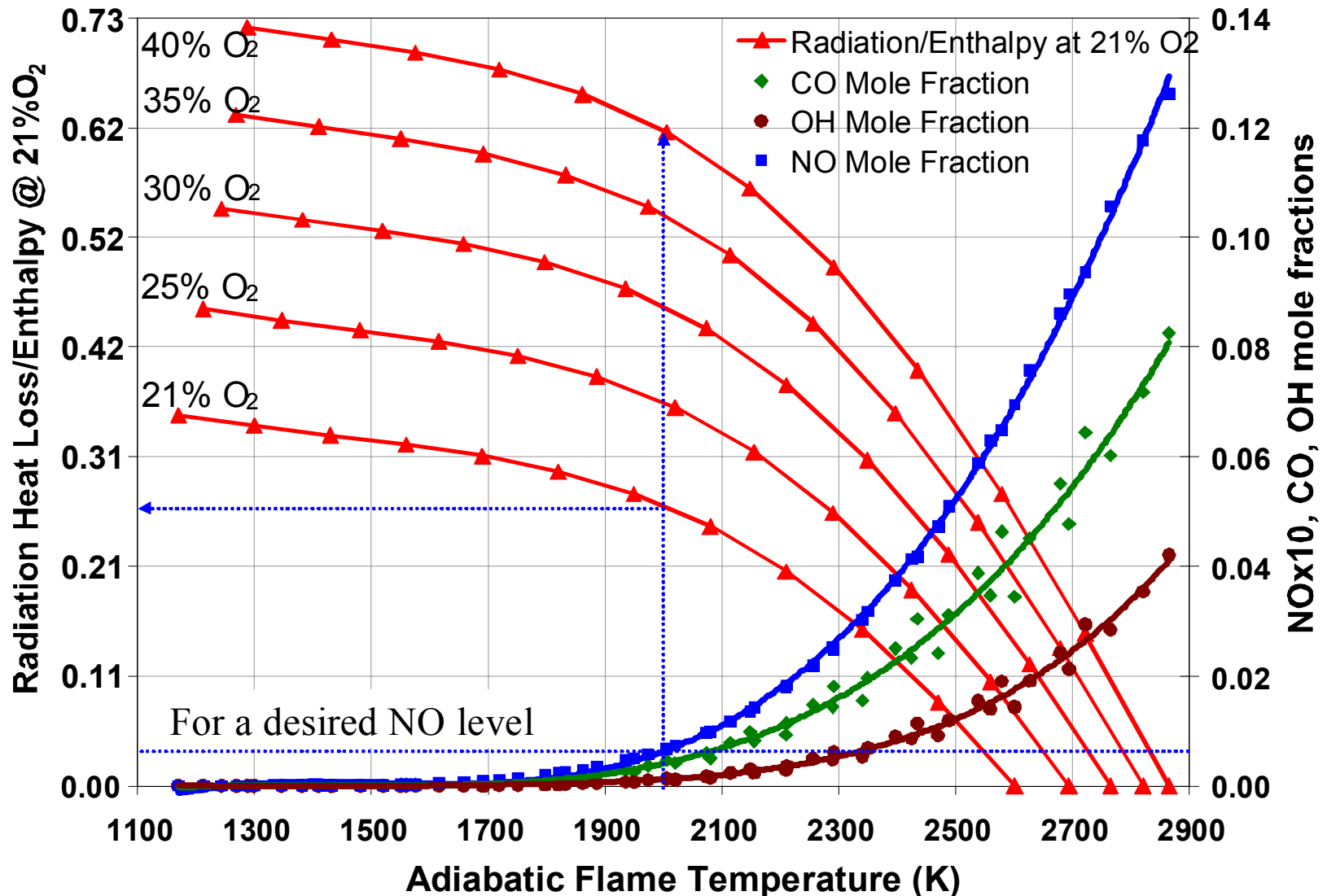
Solution to contradictory requirements:

- Transfer energy at a very high rate from the **reaction zone** to reduce high temperatures produced by O₂-enriched air.
 - This requires intensely radiating flames which are also desirable for increasing productivity (we thus need soot).
- Dilute O₂-enriched air by EGR rather than by N₂ to reduce the Flame temperature.



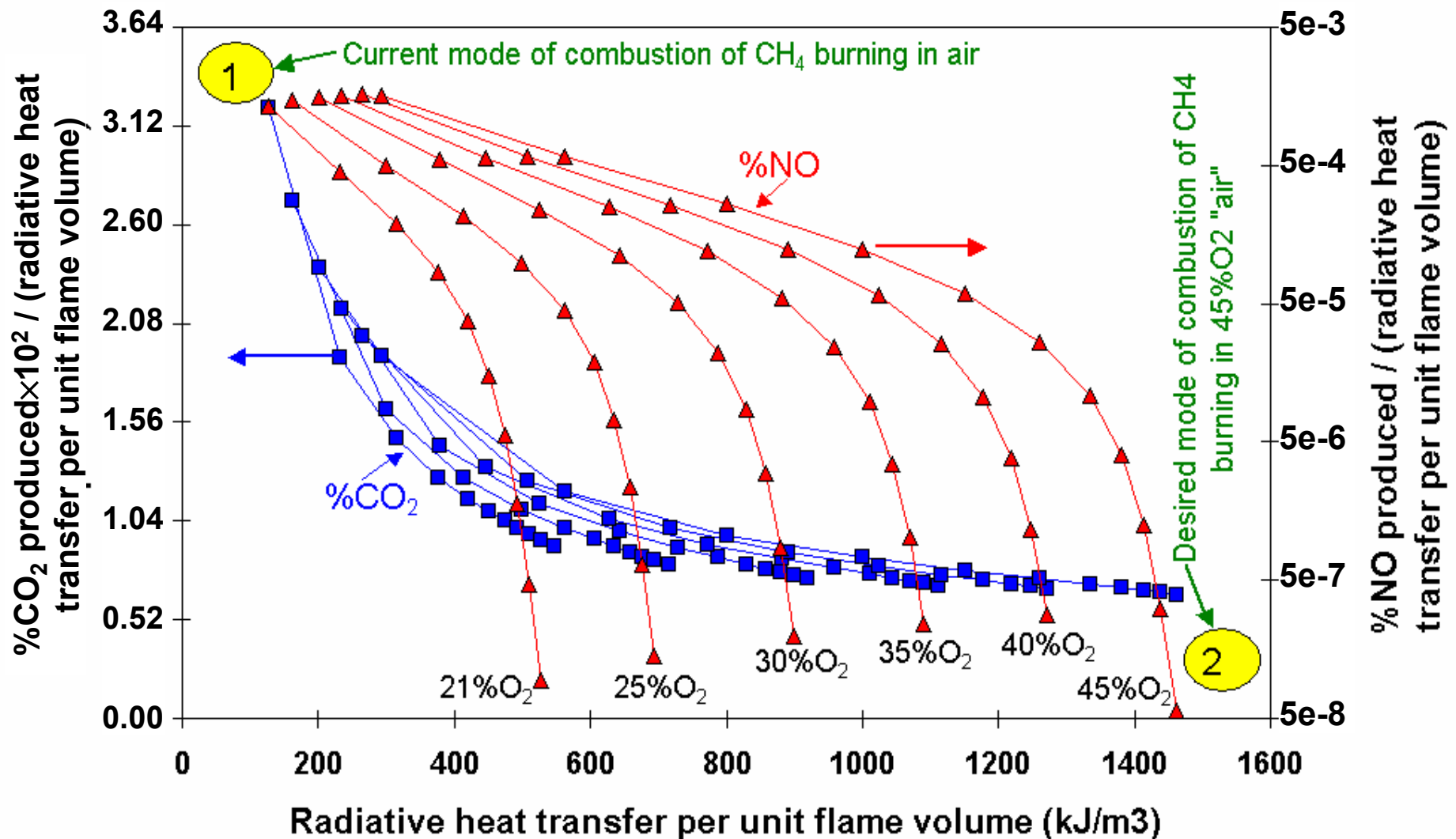
Benefits of O₂-enriched combustion & flame radiation

Equilibrium calculations for CO, NO and OH – for the same amount of CH₄ burning in “air” with different O₂% & radiation heat loss



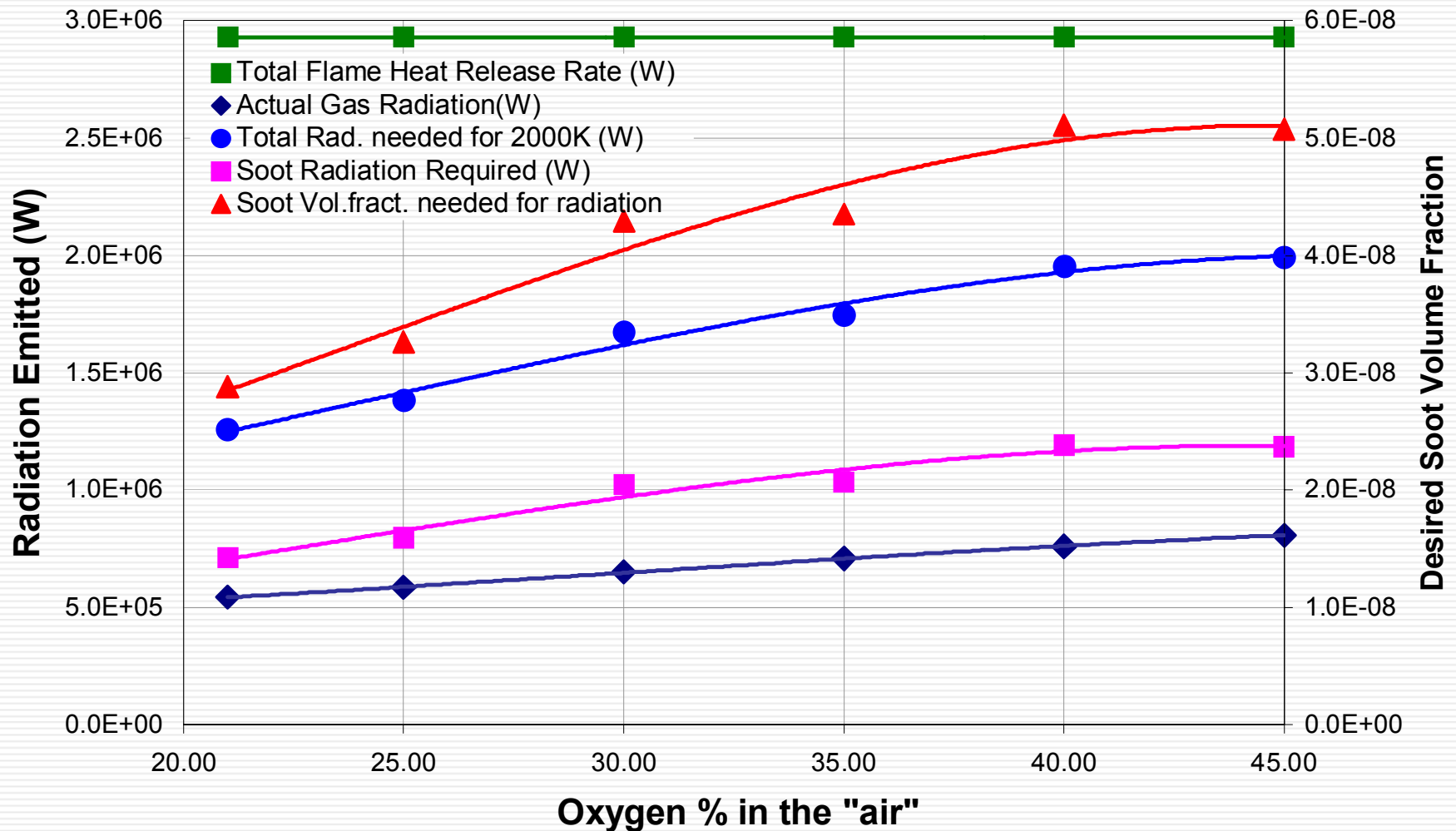
Benefits of O₂-enriched combustion & flame radiation

Equilibrium calculations for CO₂ and NO – for the same amount of CH₄ burning in “air” with different O₂% & radiation heat loss



Benefits of O_2 -enriched combustion & flame radiation

Calculations of Required Soot Volume Fraction



Summary: Benefits of O₂-enriched combustion with intense flame radiation

Increasing flame radiation:

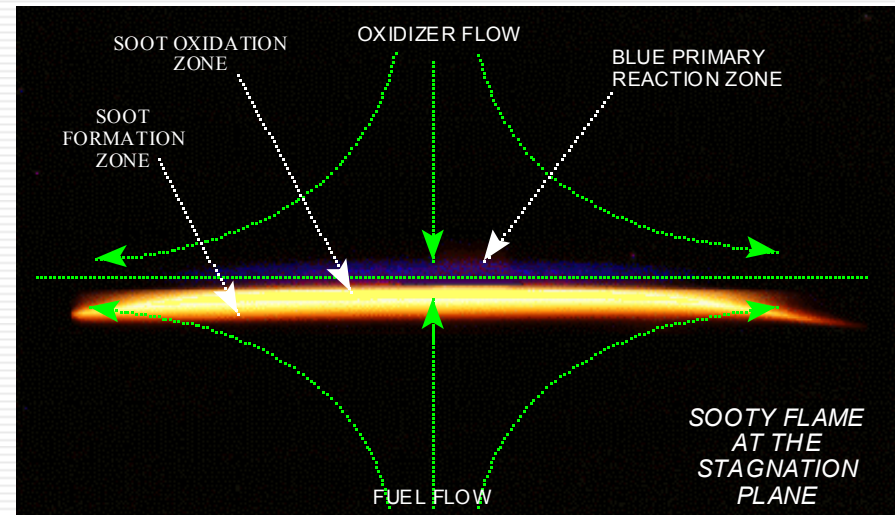
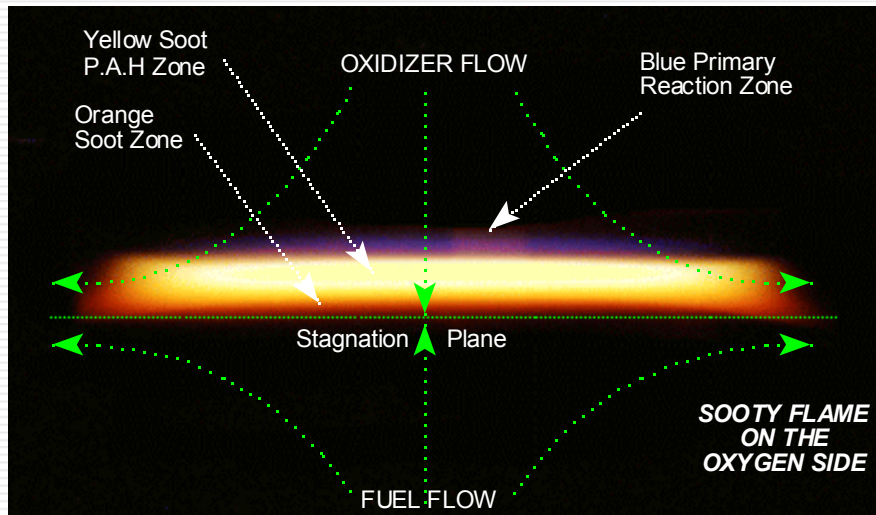
- *Decreases NO_x formation.*
- *Increases productivity (a measure of the rate at which objects are heated in the furnace) for the same fuel consumption.*
- *Decreases CO₂ production by a factor of 3 and NO by five orders of magnitude for the same fuel consumption.*
- *At 45% O₂, the required radiative fraction is 0.72.*
- *The amount of soot required is quite small (~0.05ppm), hence slightly rich conditions at a temperature of 1600K or higher are needed.*
- *Slightly rich conditions further reduce NO_x through reburn reactions.*

Thus, O₂-enriched combustion can be very useful as long as it is accompanied with high flame radiation.

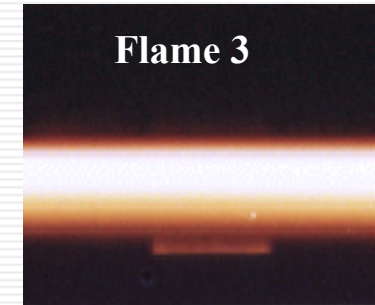
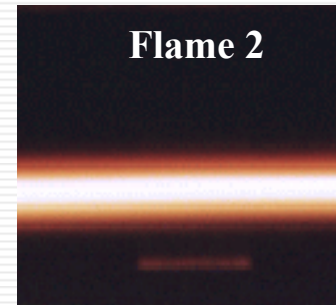
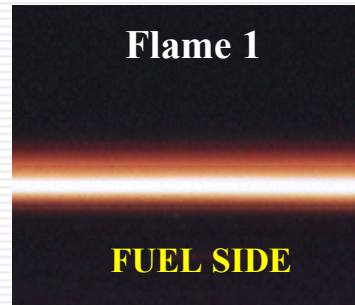
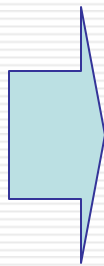


Technological challenges of O₂-enriched combustion with intense flame radiation

Configure flames that simultaneously produce and oxidize soot and have a high concentration of radiative gases (CO₂ & H₂O) in the reaction zone.



**Partially
premixed
flames**



Technological challenges of O₂-enriched combustion with intense flame radiation

Increase the volume of the reaction zone because radiation is a volumetric phenomena.

- *Need homogeneous burning.*

Larger volume inconsistent with O₂-enrichment.

- *Dilute the reactants with hot combustion products.
(Flue gas recirculation)*

Increase the residence time of the reactants

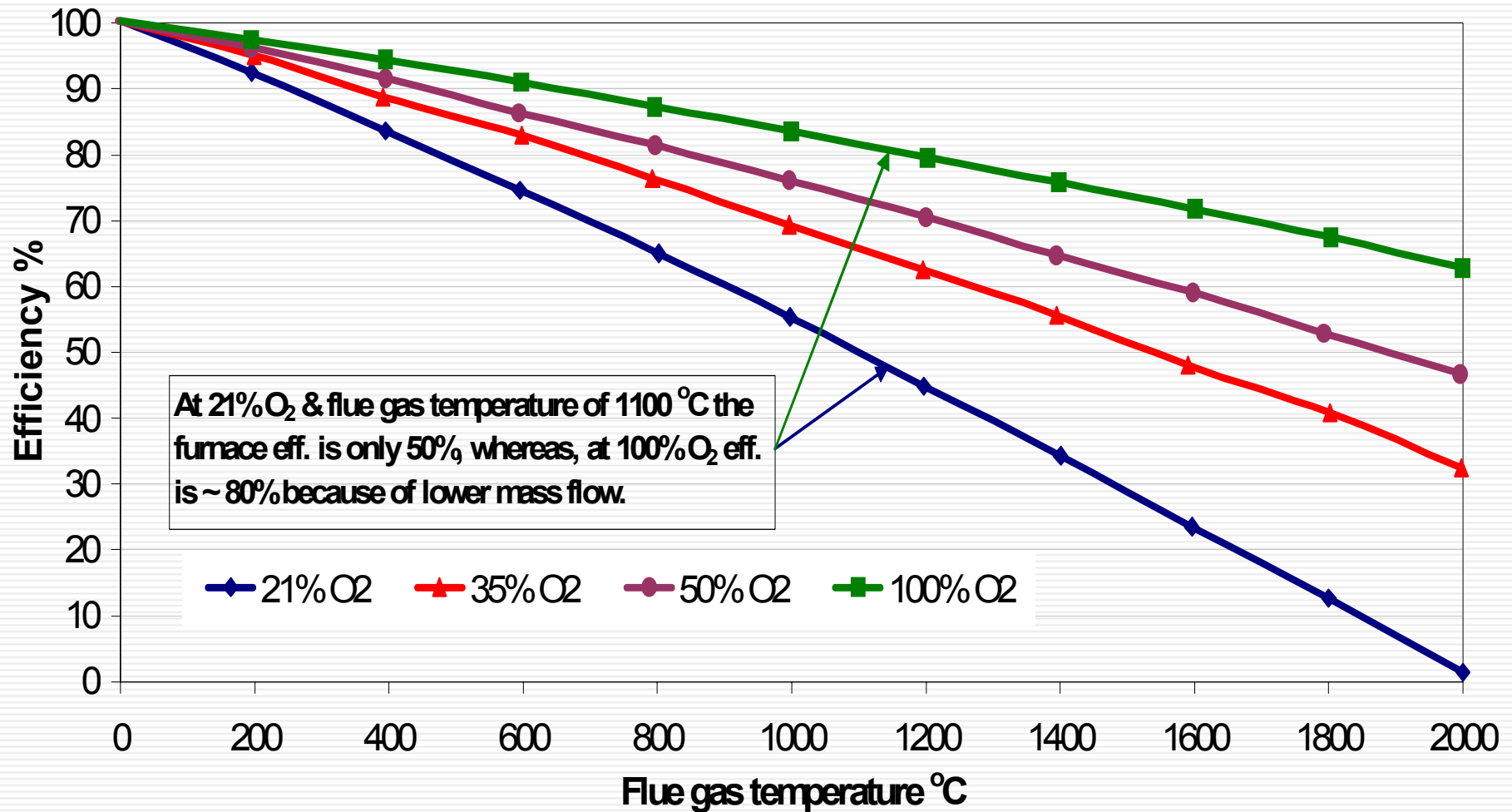
- *Reconfigure the combustion geometry.*

Increase flame stability

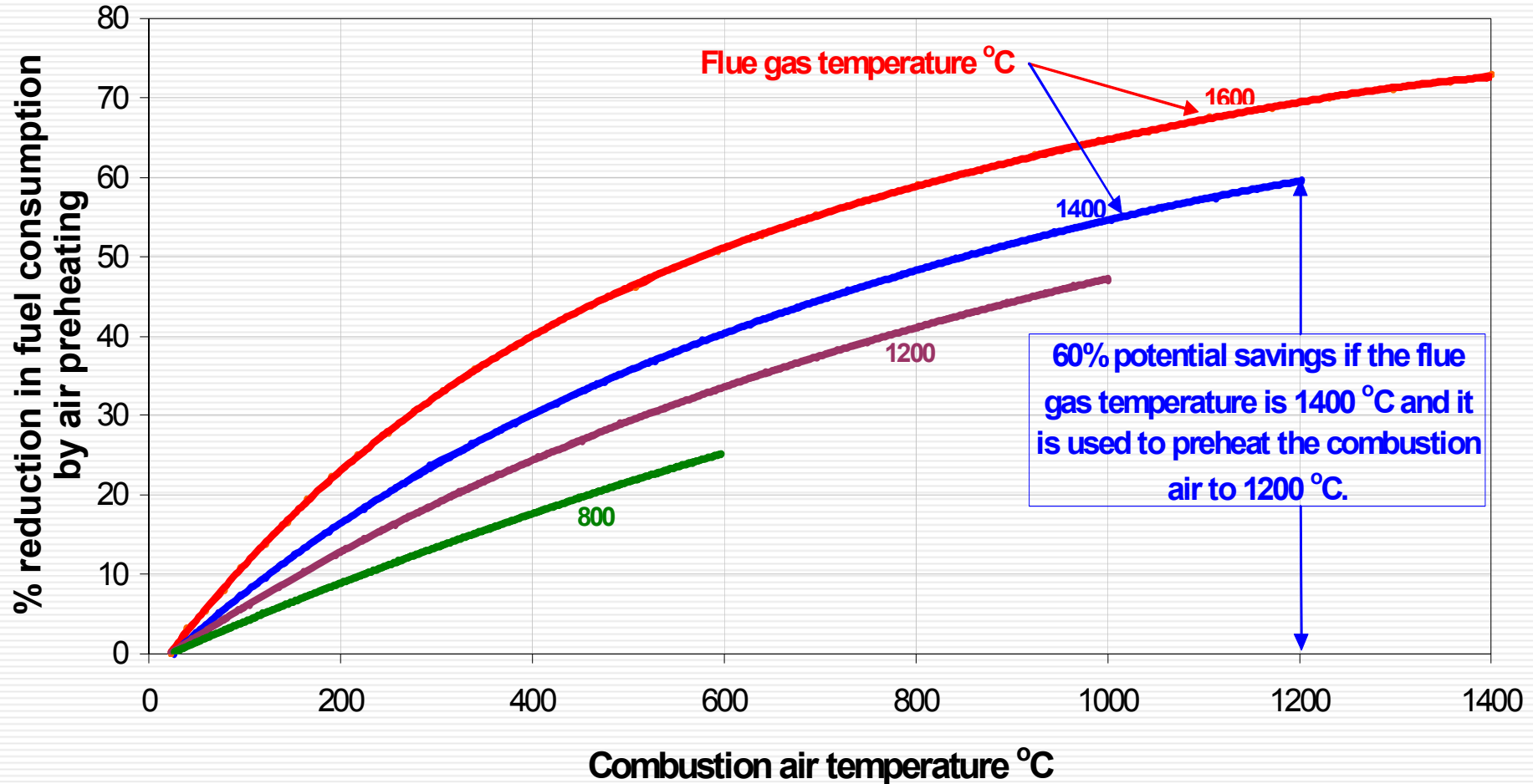
- *Reconfigure the combustion geometry (buoyant recirculation and mixing).*



Effect of flue gas temperature on efficiency for various O₂% without air preheating



Benefits of Air Preheating – reduction in fuel consumption



Benefits of Exhaust Gas Recirculation

- New combustion techniques – **DOC & FLOX** – have shown considerable promise in (**Riley et al. 2001; Wunning 1997**):
 - reducing pollutant emissions,
 - increasing furnace efficiency, and
 - providing a more uniform heat flux
- In the **DOC** concept O₂-enrichment & EGR is used without radiation.
- In the **FLOX** concept, **high regenerative preheating** (above the auto ignition temperature) of combustion air along with **excessive dilution by EGR** is utilized to enable burning in a very **low O₂ concentration atmosphere**. Hence low temperatures and NO.
- All these concepts can be profitably combined to yield additional advantages. O₂-enriched air may be used and flame temperatures may also be reduced by intense flame radiation.



Furnace Design – Salient Features

1. Capture exhaust gas enthalpy to preheat the incoming combustion air and fuel.
 - A preheat above auto ignition temperature ($>1300\text{K}$) is desirable to produce uniform distributed reaction zones and flame stability.
2. Use O_2 -enrich the air to reduce the total mass of the exhaust gases.
3. Use exhaust gas recirculation to dilute fuel & O_2 by products of combustion (EGR).
 - Highly preheated mixture can burn with low $\text{O}_2\%$ to reduce peak flame temperatures and NO . Excellent mixing of fuel with EGR & O_2 with EGR & then diluted fuel with diluted air is essential.
 - This also increases radiation uniformity in the furnace.
4. Enhance flame radiation to further reduce the peak flame temperatures
 - Added advantage: increases the furnace productivity.



Furnace Design – Salient Features

- To enhance flame radiation a high concentration of combustion products (primarily CO_2 & H_2O) and some soot is required to be present in the high temperature reaction zone. Thus, slightly rich combustion is desirable.
- The use of oxygen-enriched air increases the CO_2 & $\text{H}_2\text{O}\%$.

5. Slightly rich combustion will also enable reburn reactions to further reduce the NO production.

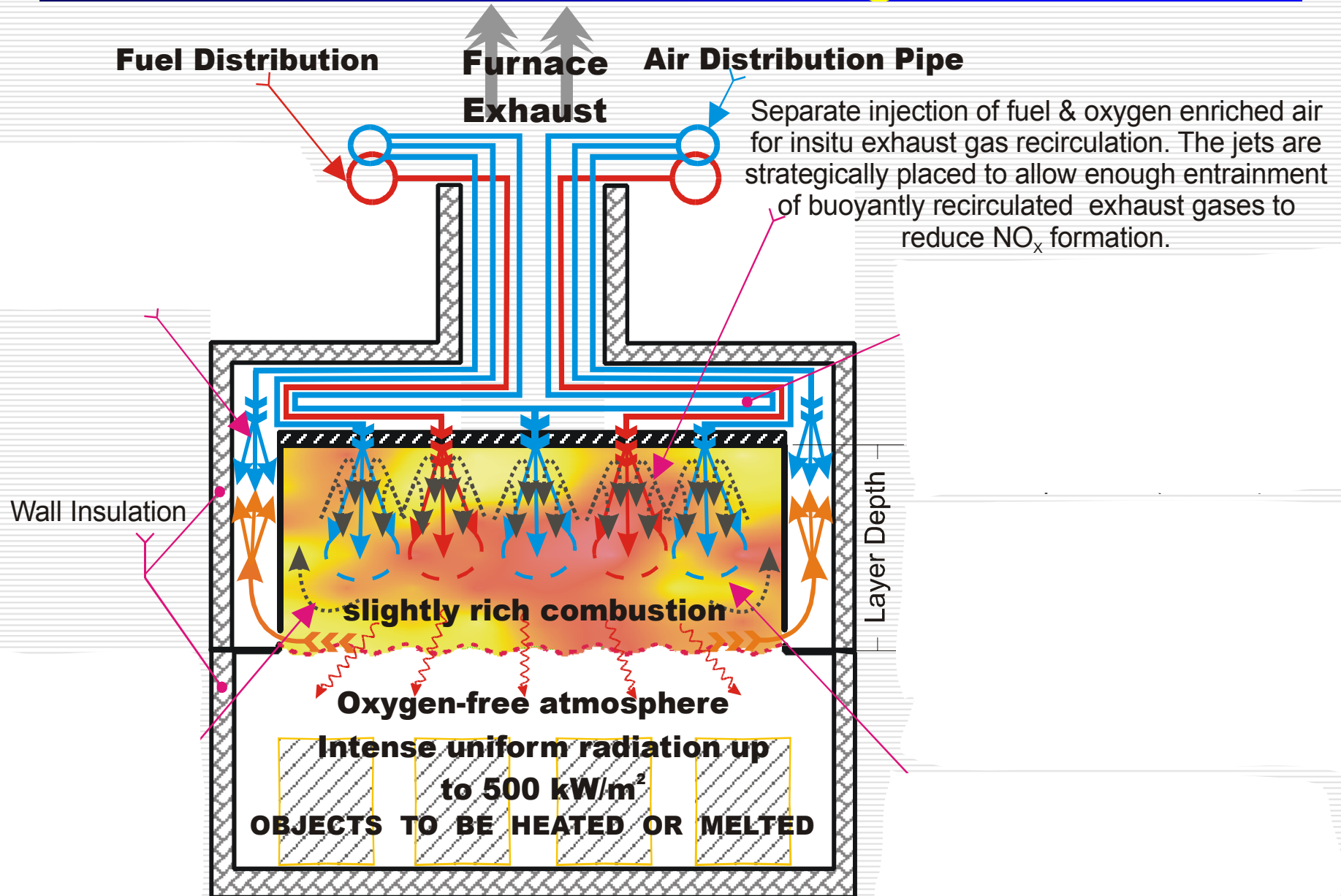
- However, it will require a second stage air injection for complete combustion.

6. To fully utilize the benefits of flame radiation, it is essential to have a substantial volume of hot combustion products.

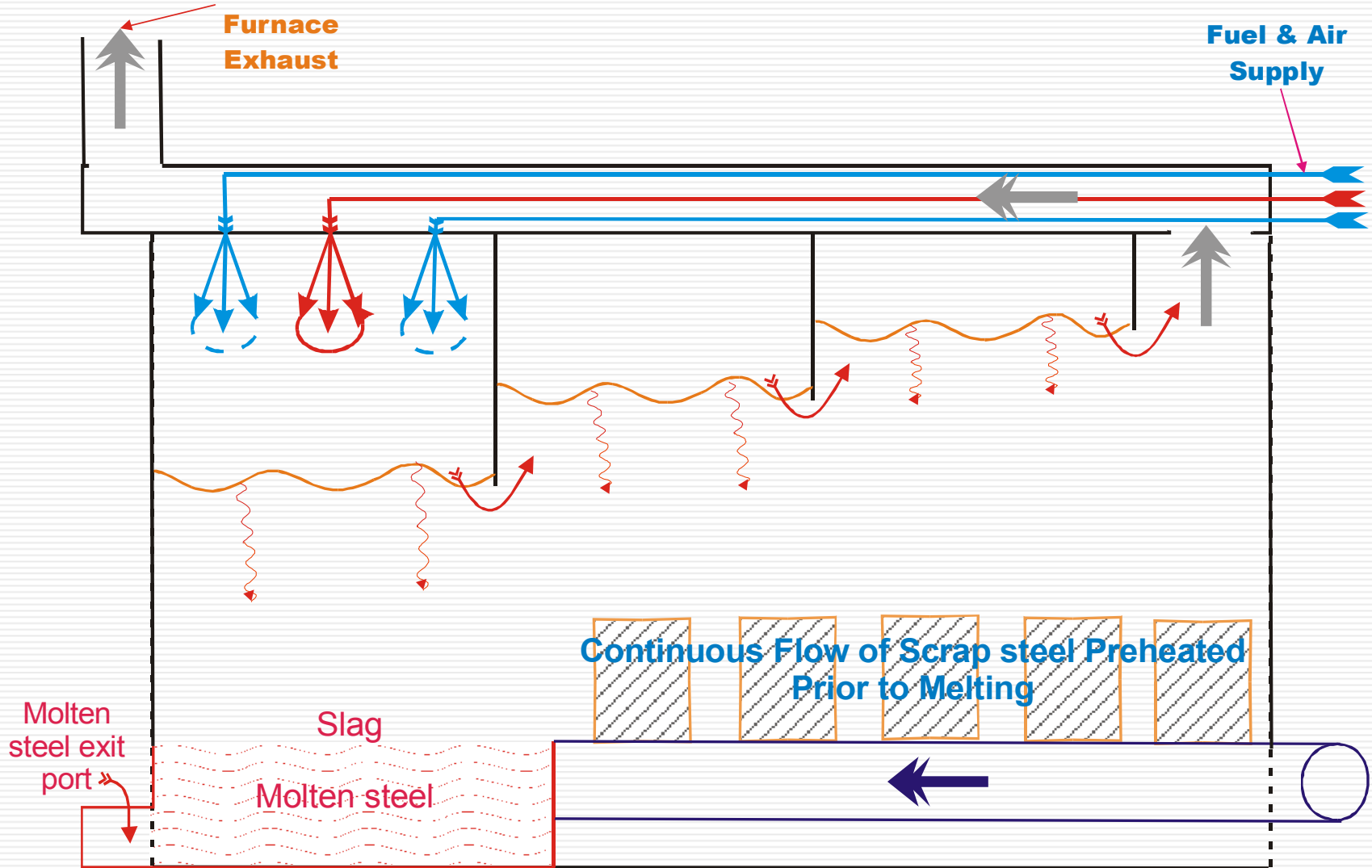
- It is also advantageous to have distributed reaction zones throughout this volume to provide uniform radiation.
- Thus, excessive mixing of the exhaust gases with the incoming air and fuel prior to reacting is essential.



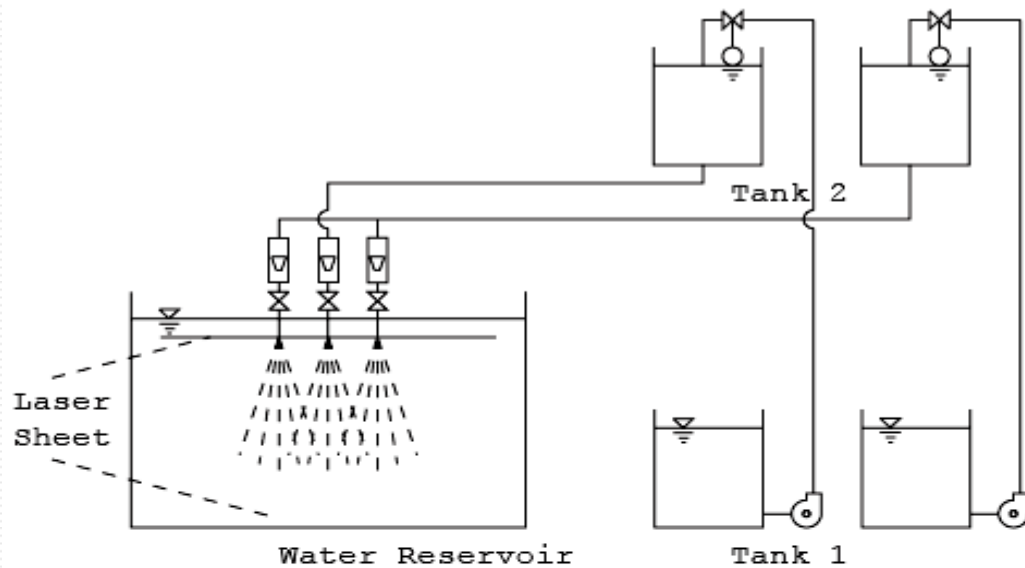
Furnace Design



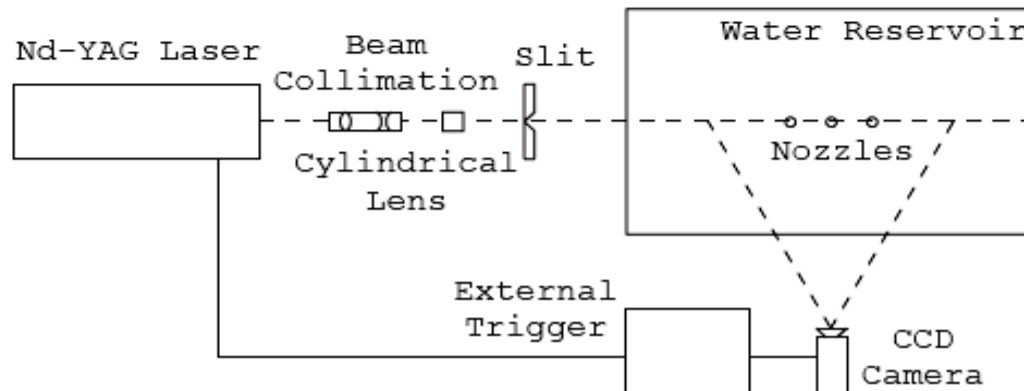
Furnace Design – continuous flow



Jet Mixing Experiments – Cold Flow



(a)

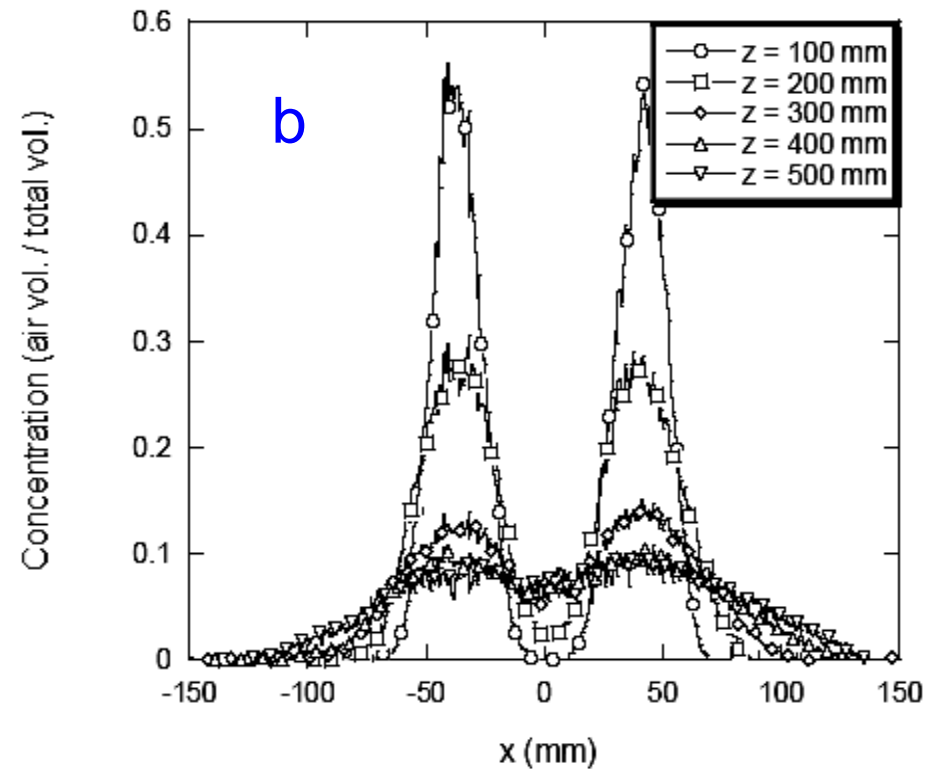
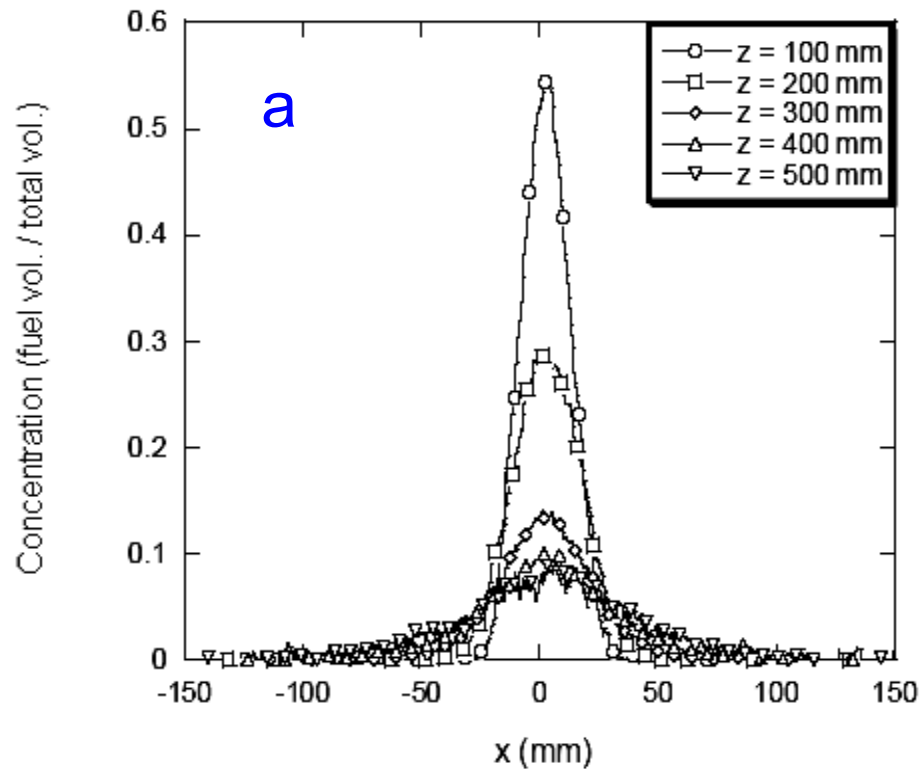


Jet Mixing Experiments – Cold Flow

Jet Mixing Experiments

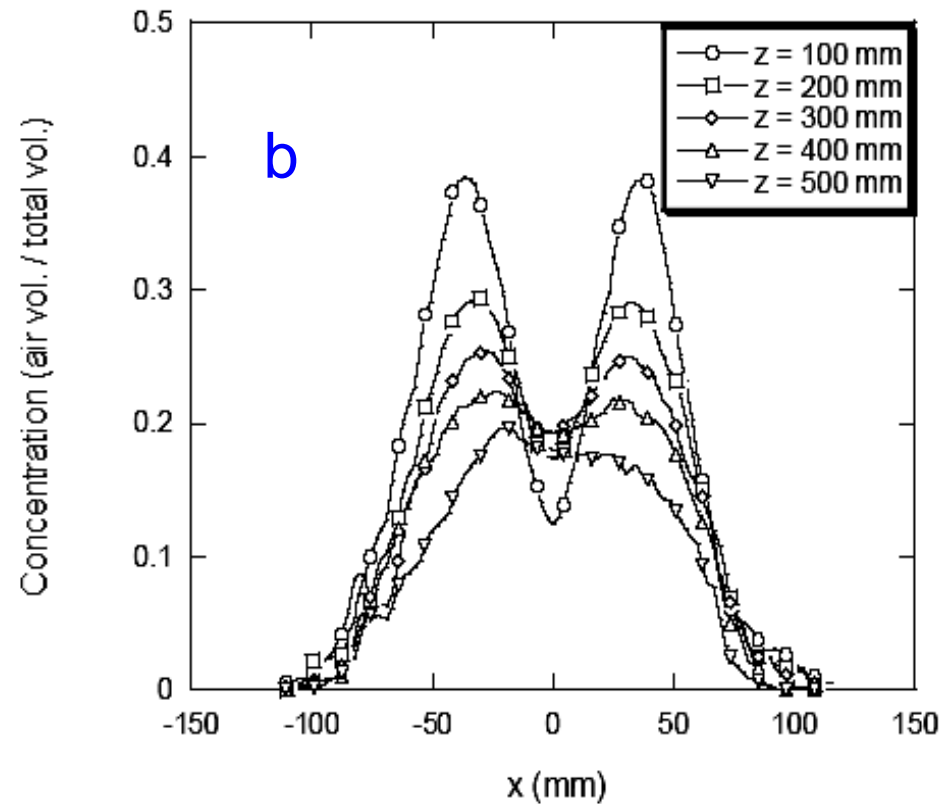
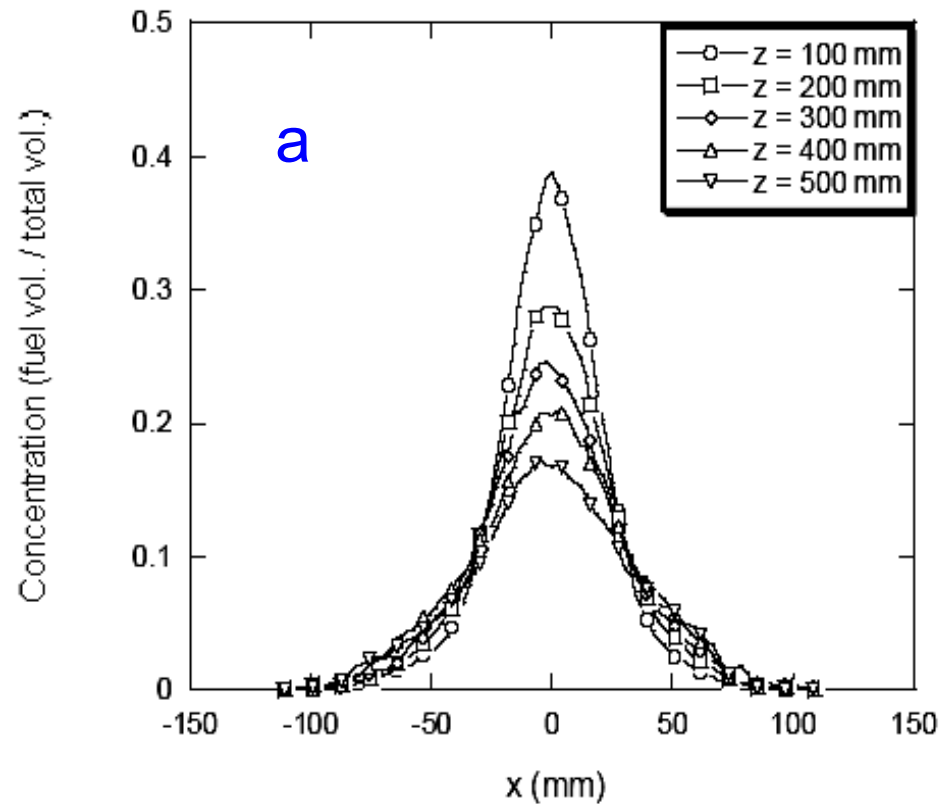


Jet Mixing Experiments – Cold Flow



Experimental data of concentration of (a) middle jet and (b) side jets for various downstream distance at $s = 38.1$ mm

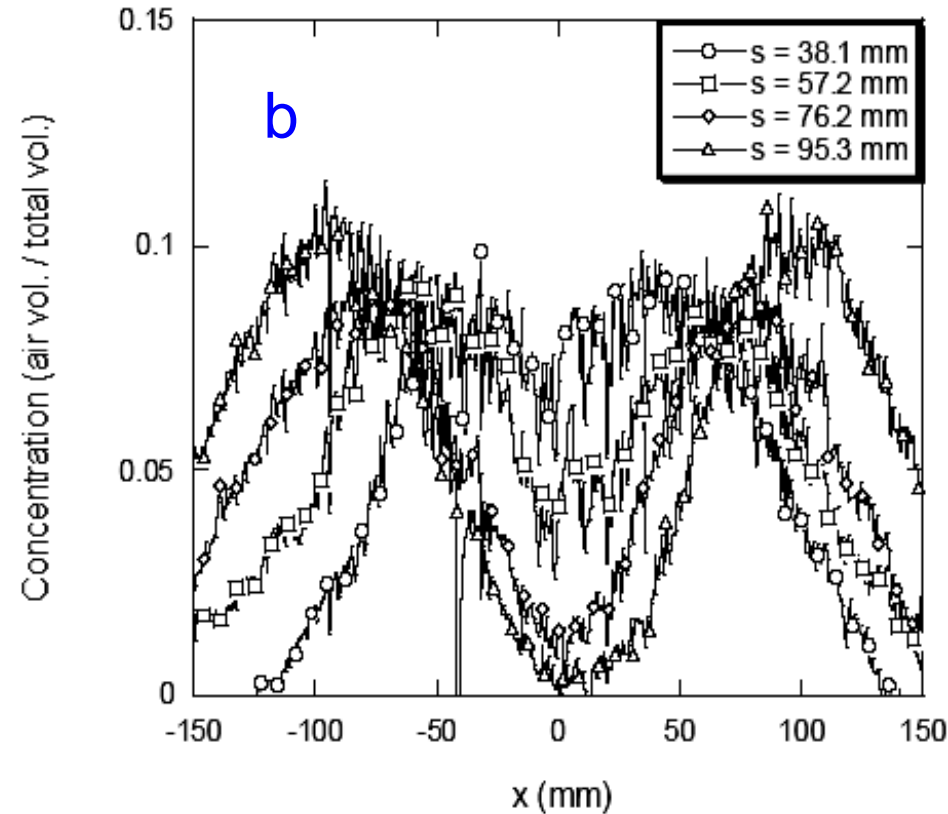
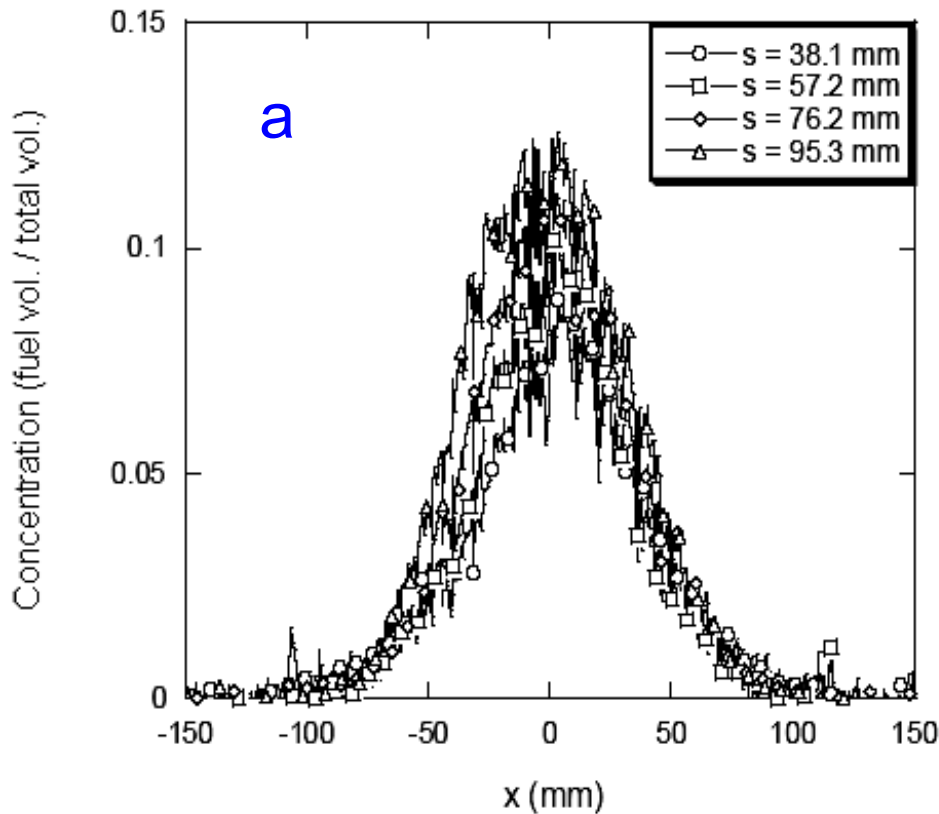
Jet Mixing Experiments – Cold Flow



Numerical results for concentration of (a) middle jet and (b) side jets for various downstream distance at $s = 38.1$ mm



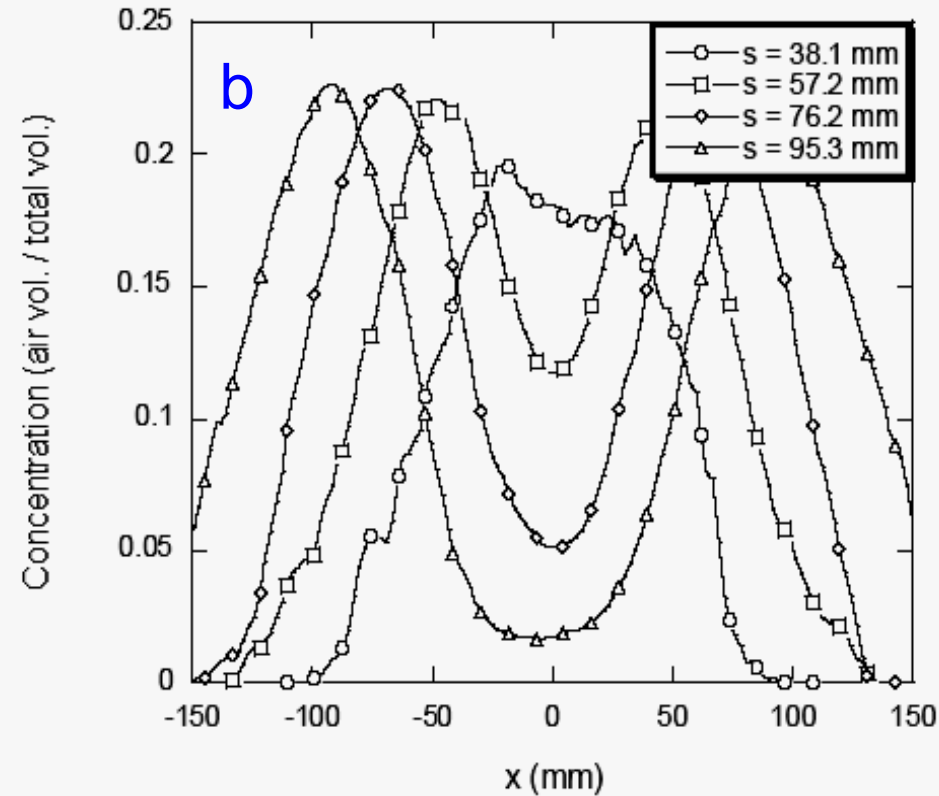
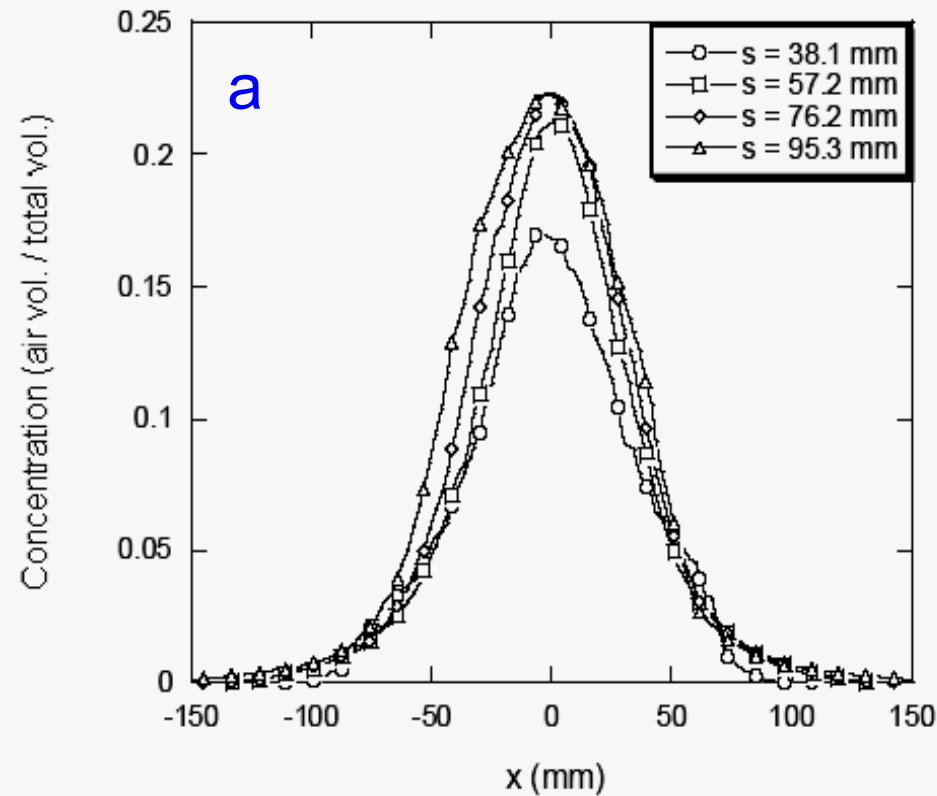
Jet Mixing Experiments – Cold Flow



Experimental data of concentration of (a) middle jet and (b) side jets for various separation at $z = 500$ mm



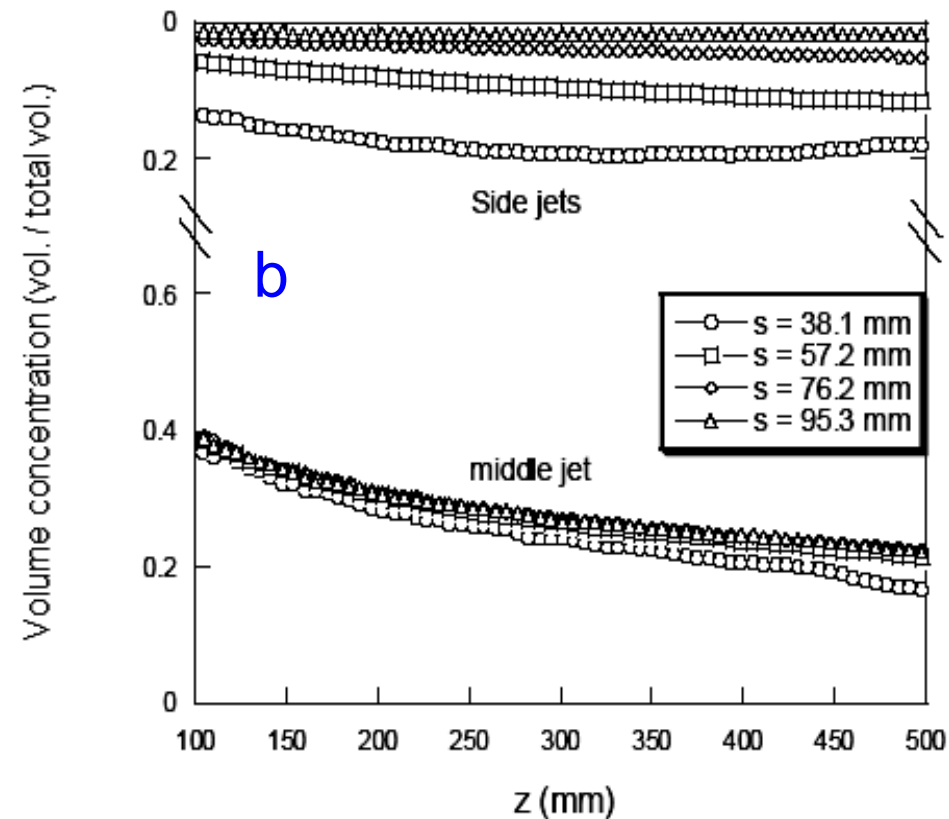
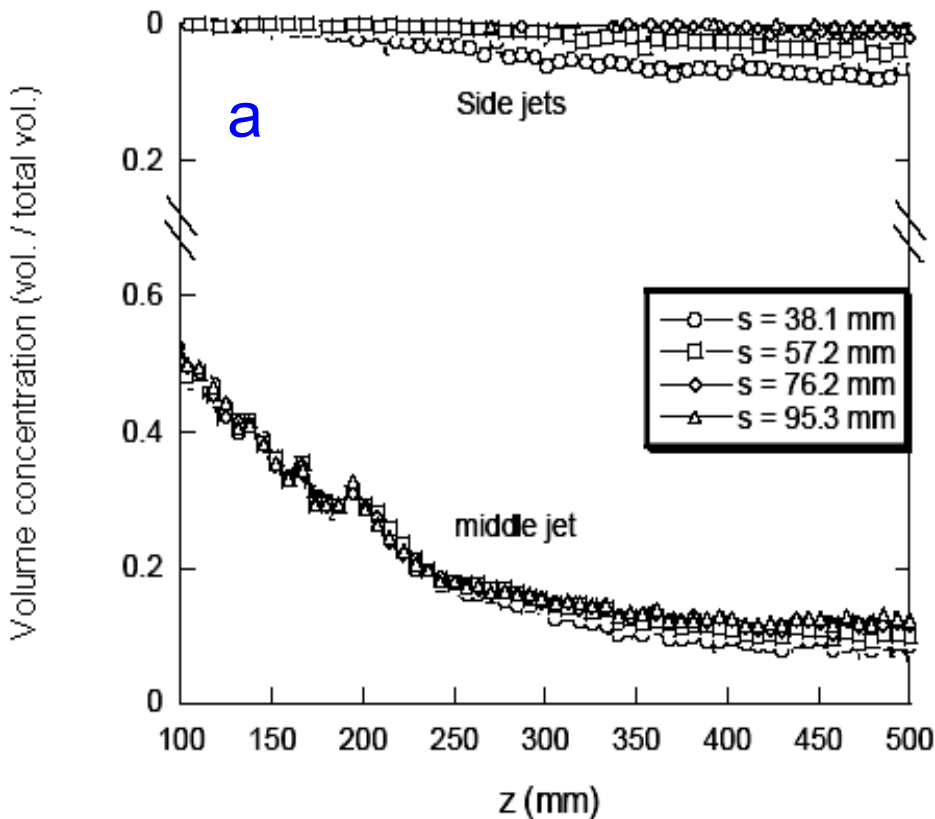
Jet Mixing Experiments – Cold Flow



Numerical results for concentration of (a) middle jet and (b) side jets for various separation at $z = 500$ mm



Jet Mixing Experiments – Cold Flow



Centerline ($x = 0$) concentration of middle and side jets for various separation distances from (a) experiments and (b) simulations

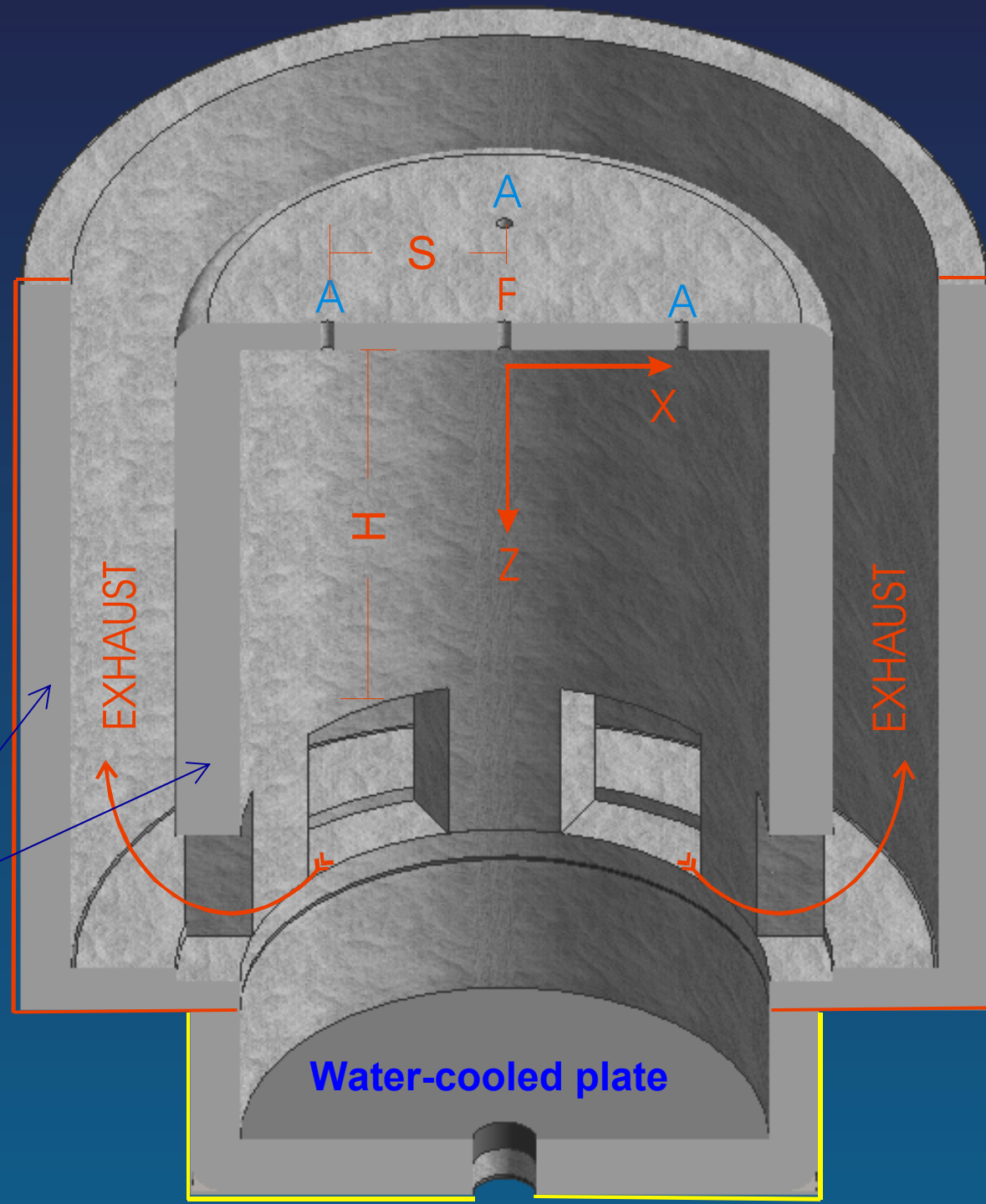


Experimental Furnace (Hot Flow)

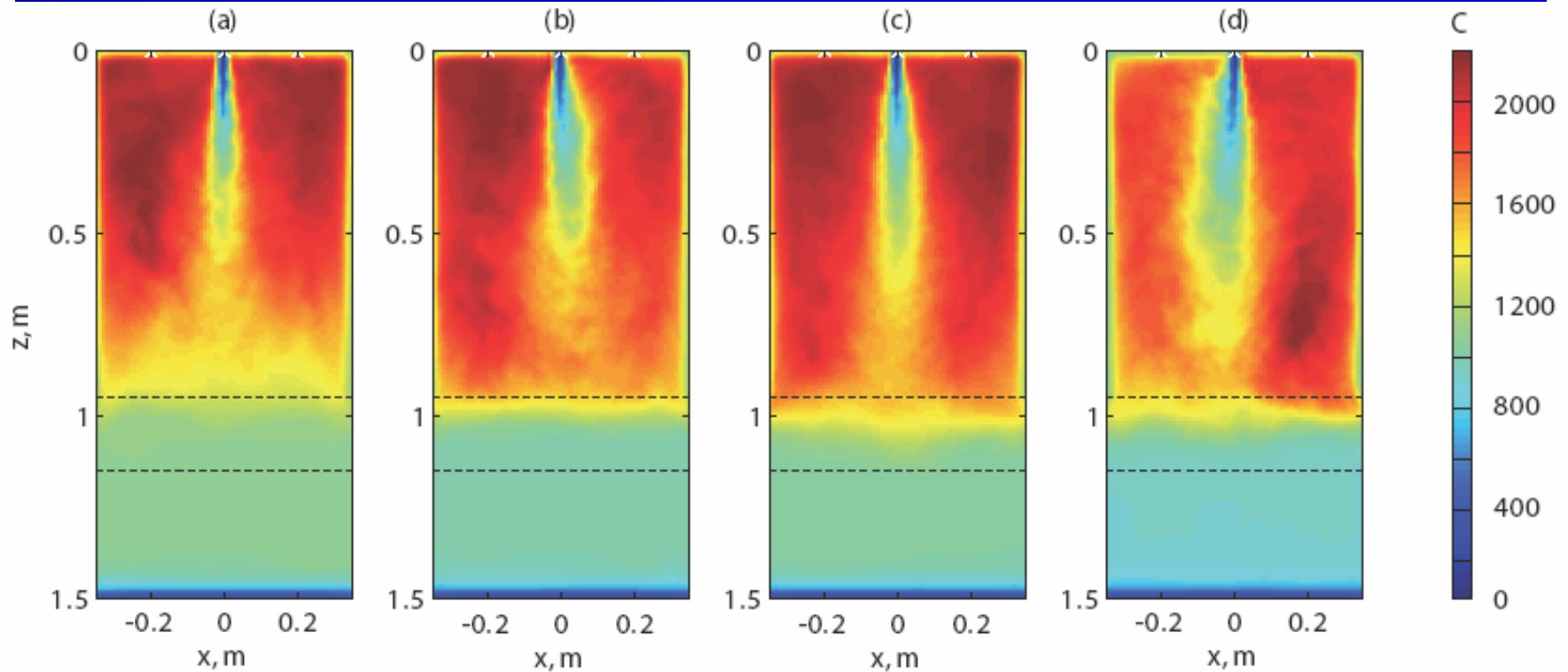
Variables to be optimized are:

- Fuel and air velocities (v).
- Fuel and oxidizer nozzle separation distance (S).
- Nozzle diameter (d).
- Fuel and oxidizer concentrations (χ).
- Fuel heating value and stoichiometry (HV).
- Hot layer depth (H).

High
Temperature
Ceramic



Furnace Modeling – Hot Flow – const. $\rho(dv)^2$

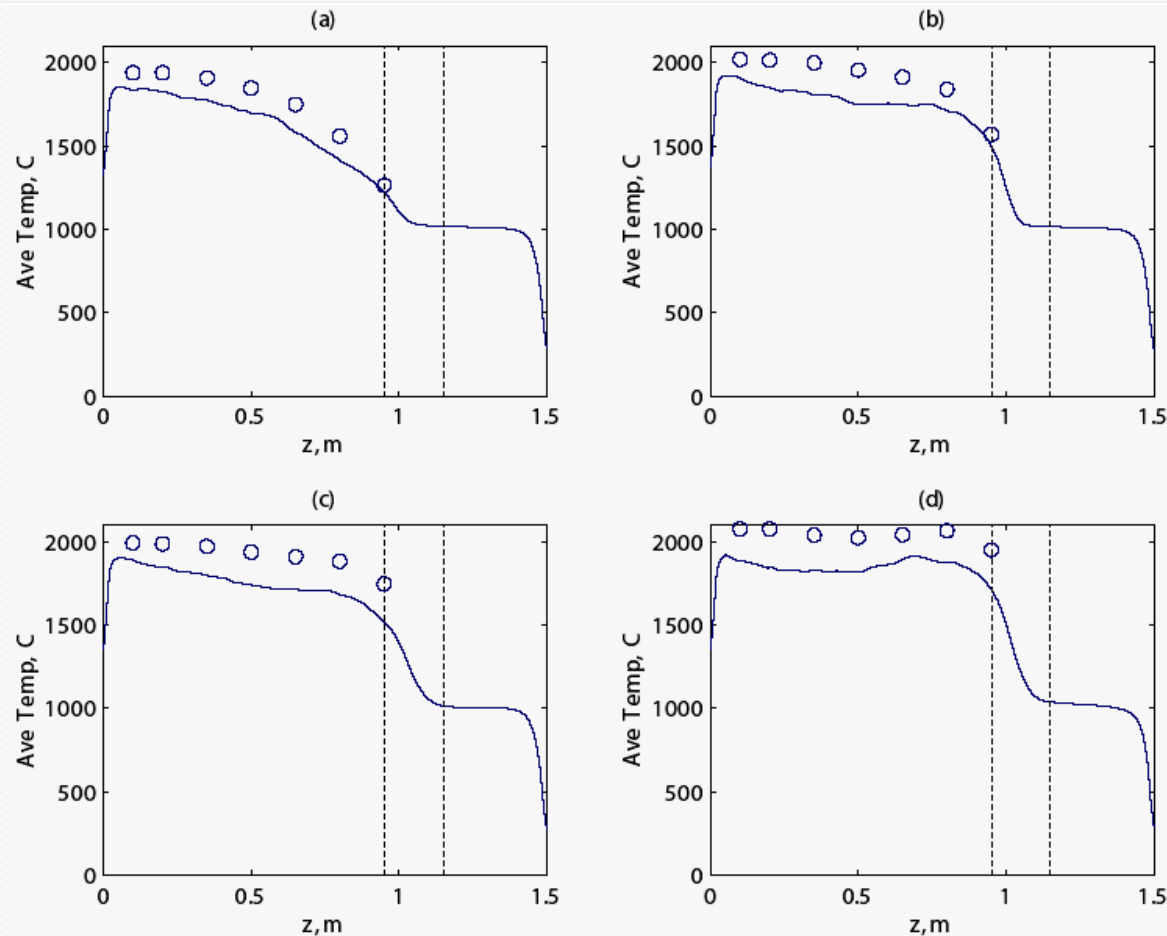


Time averaged temperature in the x-z plane

- $d_{fuel} = 2.19 \text{ cm}$, $v = 3.0 \text{ m/s}$; $d_{air} = 5.12 \text{ cm}$ $v = 1.45 \text{ m/s}$;
- $d_{fuel} = 1.90 \text{ cm}$, $v = 4.0 \text{ m/s}$, $d_{air} = 4.43 \text{ cm}$ $v = 1.93 \text{ m/s}$;
- $d_{fuel} = 1.69 \text{ cm}$, $v = 5.0 \text{ m/s}$, $d_{air} = 3.97 \text{ cm}$ $v = 2.42 \text{ m/s}$;
- $d_{fuel} = 1.55 \text{ cm}$, $v = 6.0 \text{ m/s}$, $d_{air} = 3.62 \text{ cm}$ $v = 2.9 \text{ m/s}$.



Furnace Modeling – Hot Flow – const. $\rho(dv)^2$

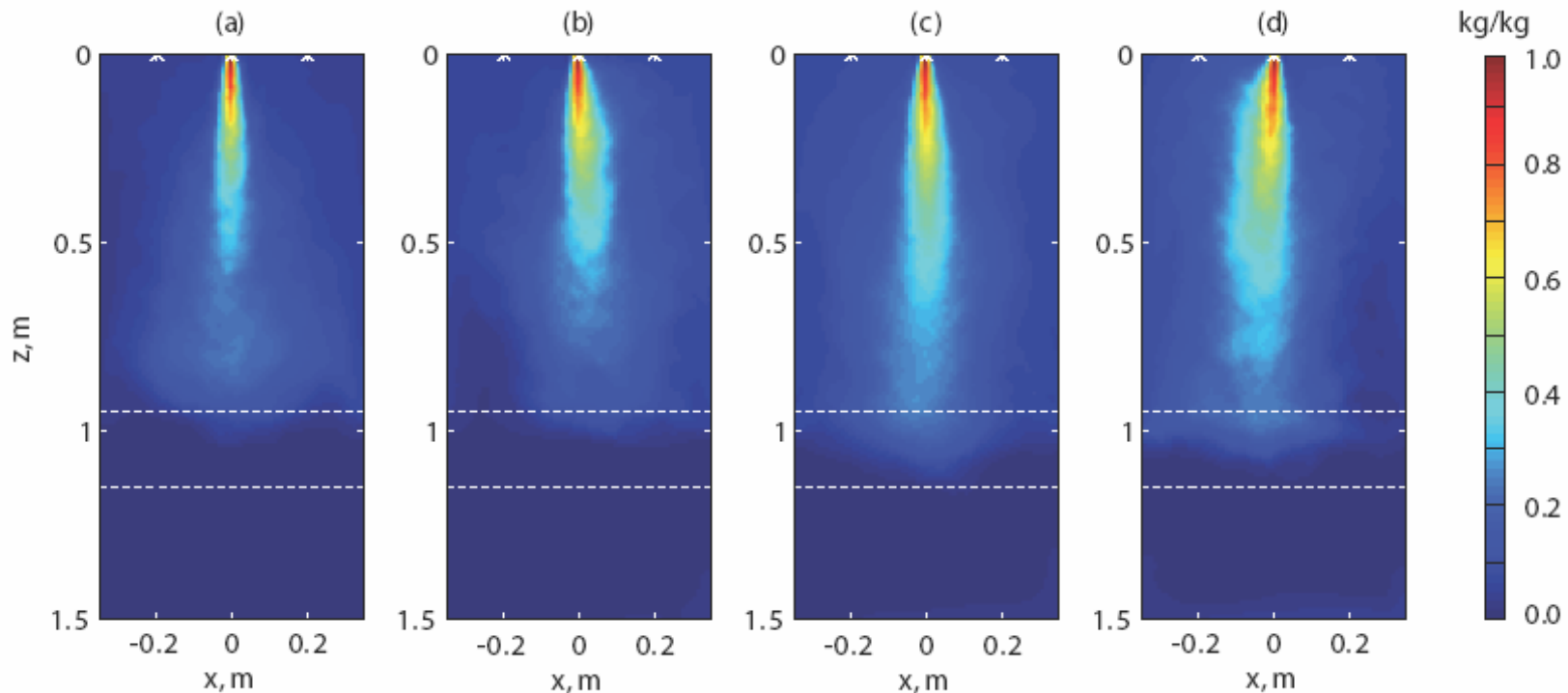


Lines: Time averaged temp for the same z in the x-z plane.

Circles: Time averaged temp over x-y planes for same z.



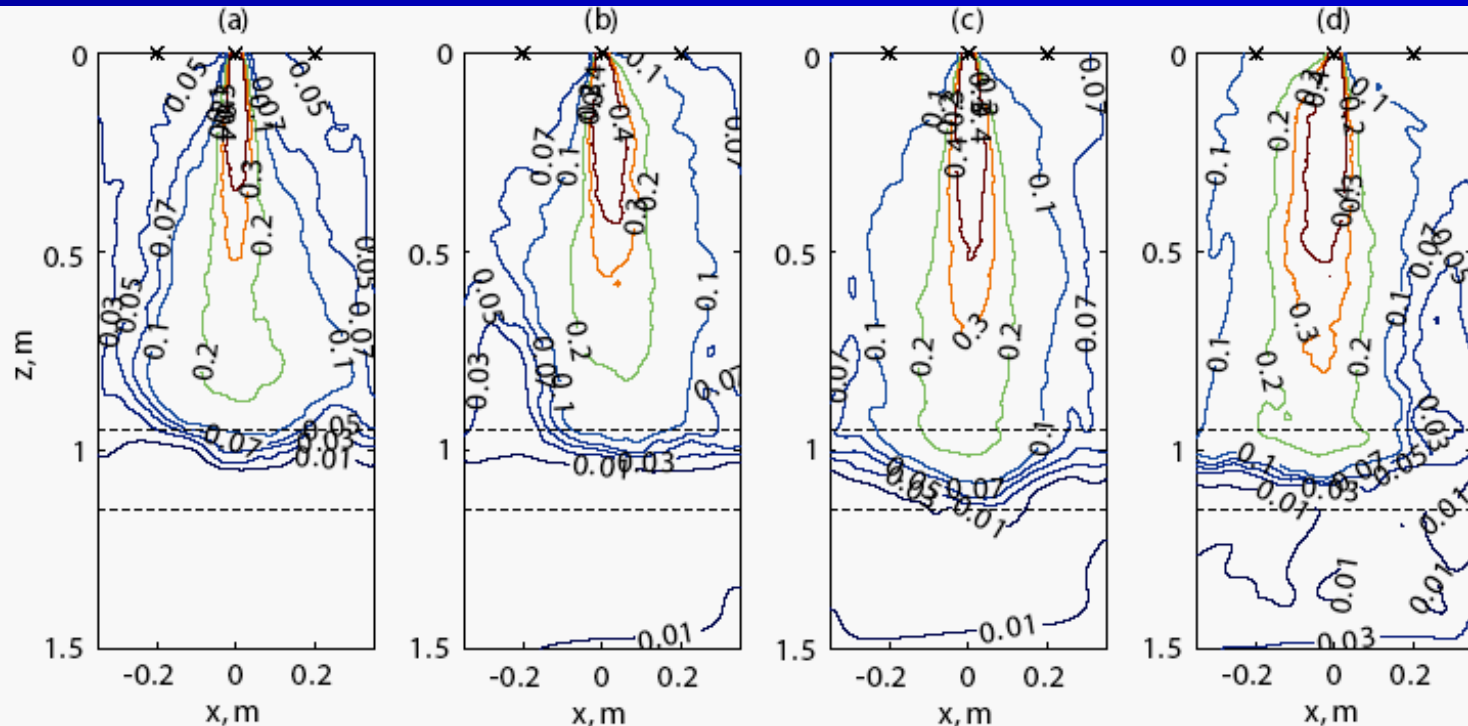
Furnace Modeling – Hot Flow – const. $\rho(dv)^2$



Time averaged fuel (kg fuel/kg total) in the x-z plane

- $d_{fuel} = 2.19 \text{ cm}$, $v = 3.0 \text{ m/s}$; $d_{air} = 5.12 \text{ cm}$ $v = 1.45 \text{ m/s}$;
- $d_{fuel} = 1.90 \text{ cm}$, $v = 4.0 \text{ m/s}$, $d_{air} = 4.43 \text{ cm}$ $v = 1.93 \text{ m/s}$;
- $d_{fuel} = 1.69 \text{ cm}$, $v = 5.0 \text{ m/s}$, $d_{air} = 3.97 \text{ cm}$ $v = 2.42 \text{ m/s}$;
- $d_{fuel} = 1.55 \text{ cm}$, $v = 6.0 \text{ m/s}$, $d_{air} = 3.62 \text{ cm}$ $v = 2.9 \text{ m/s}$.

Furnace Modeling – Hot Flow – const. $\rho(dv)^2$



Time averaged) iso-concentration lines in the x-z plane

- $d_{fuel} = 2.19 \text{ cm}$, $v = 3.0 \text{ m/s}$; $d_{air} = 5.12 \text{ cm}$ $v = 1.45 \text{ m/s}$;
- $d_{fuel} = 1.90 \text{ cm}$, $v = 4.0 \text{ m/s}$, $d_{air} = 4.43 \text{ cm}$ $v = 1.93 \text{ m/s}$;
- $d_{fuel} = 1.69 \text{ cm}$, $v = 5.0 \text{ m/s}$, $d_{air} = 3.97 \text{ cm}$ $v = 2.42 \text{ m/s}$;
- $d_{fuel} = 1.55 \text{ cm}$, $v = 6.0 \text{ m/s}$, $d_{air} = 3.62 \text{ cm}$ $v = 2.9 \text{ m/s}$.

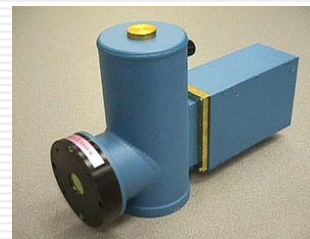
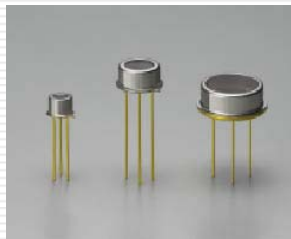
Furnace Modeling – Hot Flow

LES Computer Models – Hot Flow



Real-time Furnace Control

- Smart fast-response detectors are needed for real-time furnace control.
- To achieve this goal, two systems are developed to study the emission spectroscopy of combustion products.
 - **Photodetector array**--provides temporally and spectrally resolved combustion product data.
 - **Infrared camera**--provides temporally and spatially resolved images within a particular wavelength.



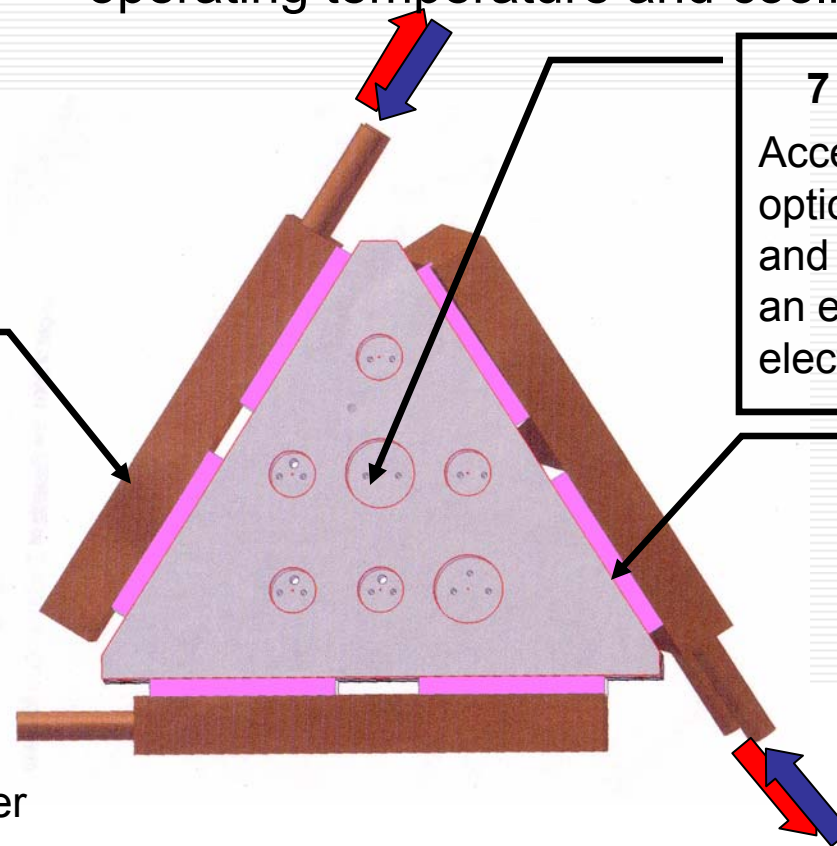
Photodetector Assembly: Design Layout & Components



L = 5.5in (14cm)

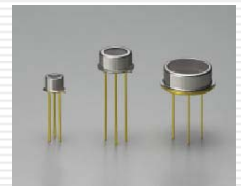
Design Goals

- To package sensors and filters → focus view of the detector
- To minimize the size while maximizing the number of thermal electric coolers (TEC) → Reduce operating temperature and cooling time



7 Photodetectors

Accepts an optical signal and produces an equivalent electrical signal



3 Heat exchangers



Dissipates heat from hot side of TEC

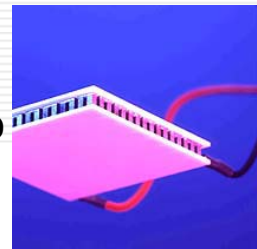
Heated water



Cooling water


6 Thermal electric cooling modules (TEC)

Cools block to -20°C (-4°F)



Photodetector Assembly: Filter Selection & Species Summary

- An array of photodetectors have been chosen to detect species from the ultraviolet (UV), visible (VIS), and infrared (IR) regions.
- Filters are chosen for select products of combustion.



Detector	Detector Wavelength (nm)	Species (Emission Peak–nm)	Filter Bandwidth (nm)
Si	190-1000	OH (306.4) CH (314-390) NO (320, 338)	260-400
Si	190-1000	Soot	600-1200
InGaAs	900-1700	Soot	225-2700
PbS	1000-3000	Soot	1910-2350
PbS	1000-3000	CO ₂ (2700) H ₂ O (2600)	2613-2837
PbSe	1500-5000	CH ₄ (3320)	3265-3555
PbSe	1500-5000	CO ₂ (4260)	4200-4400

Budget History and Projection

Phase / Budget Period		ITP	Cost Share total	Cost Share University	Cost Share Industry
From	To				
7/1/02	6/30/03	156,495	45,836	37,836	8,000
7/1/03	6/30/04	169,191	43,365	36,045	7,320
7/1/04	6/30/05	131,653	37,500	25,500	12,000
Additional Request		100,000	25,000	22,600	2,400
Totals		557,339	151,701	121,981	29,720



Future Plans

1. Complete furnace measurements and calculations for various v , d , S , H and fuel and oxidizer concentrations and stoichiometry.
2. Make gas temperature, gas composition and total and spectral radiation measurements.
3. Develop furnace control methodology based on the measurements.
4. Design and Measurement Iterations.
5. Modify design based on Industry Advisory Group (IAG) suggestions.



Commercialization Plans

We have established an Industrial Advisory Group (IAG) that is growing.

We expect greater enthusiasm once the 50kW lab-scale furnace is demonstrated and measurements shown.

This lab furnace awaits University safety approval. The current members of IAG are:

1. Dow Corning
2. Visteon Corporation
3. Delphi Corporation
4. Atmosphere Annealing
5. American Axel Manufacturing
6. Detroit Thermal
7. Inducto Heat Inc.
8. Wis Furnaces
9. Detroit Energy
10. Climax Research
11. NCMS
12. Kettering University



CONCLUSIONS

The present design offers the following benefits:

1. Reduction in energy costs.
2. Reduction in greenhouse gas emissions.
3. Reduction in NOx emissions.
4. Increase in productivity.
5. Use of calorific value fuels.
6. Multi-fuel capability.
7. Oxygen-free atmosphere to prevent oxidation.
8. Potential for in situ incineration of volatile organic compounds.

